Chapter 1

Recent Trends in Heavy Flavour Hadron Physics

1.1 Introduction

The field of hadron physics contains the study of strongly interacting matter in all its manifestations and understanding of its properties and interactions in terms of the underlying fundamental theory, Quantum Chromodynamics (QCD). The primary goal of hadron physics are to determine the relevant degrees of freedom that govern the hadron phenomena at all scales, to establish the connection of these degrees of freedom to the parameters and fundamental fields of QCD to quantitatively describe a wide array of hadron phenomena, ranging from its spectroscopy to their decay properties. Spectroscopy is a powerful tool in physics as it provides a mean to understand the essential degree of freedom involved in molecules, atoms, nucleus and the hadrons. For example, the color degree of freedom emerged from detailed baryon spectroscopy and flavor symmetry was first seen clearly in hadron spectroscopy. The hadron structure can be viewed in the rest frame; which is appropriate for consideration of spectroscopy and measurements of quantities like the charge radius, magnetic moment, etc. The quarkonia spectra solidified our belief in the existence of quarks and provided enough evidences for the confinement of quarks and antiquarks within the hadrons. Hadron spectroscopy will continue to be a key tool in our efforts to understand the long-wavelength degrees of freedom in Quantum Chromodynamics (QCD). The long-range properties of QCD are central to the issues of this subfield, bringing into play its full complexity and a set of rich phenomena in strong interactions. The properties of QCD and the nature of confinement are among the few outstanding
open problems in hadron physics. To get a coherent picture, contributions from phe-nomenology, QCD-based models and lattice gauge theory (LGT) are being employed. Hadron spectroscopy cannot be explained using standard perturbation theory. Non-perturbative field theoretic methods as well as phenomenological model studies play crucial role to gain understanding from the experimental data. The field has a long history, starting with phenomenological descriptions of hadrons and their interactions, the hadron spectrum, heavy quark symmetry, effective field theory, the quark-gluon plasma and novel color superconducting phases of matter etc., are different attempts the efforts to understand the behavior of QCD at the hadronic scale, among a host of others [1, 2, 3]. Although many of its deepest questions remain unresolved for decades.

We have now within our grasp unprecedented opportunities for fundamental progress. Recent advances in computational technology, lattice field theory algorithms, continuum model building, accelerator beam qualities and detector designs have led us to the threshold of knowing more about the fundamental properties of QCD and improving the ability to understand more about the nonperturbative QCD quantitatively in the domain of hadrons [1, 2, 3].

Many years ago, the discovery of approximate SU(3) symmetry in the light flavour sector (up, down and strange) led to a breakthrough in establishing the quark model. As more detailed information about the existence of heavy flavour like charm and beauty became available, the discussion evolved into the issues of interquark forces and details of the heavy flavour hadron spectroscopy led to the extension of SU(3) flavour symmetry to SU(4) and SU(N_f). This extension of SU(N_f) symmetry to incorporate charm and beauty flavour quarks led to an increase in the number of hadrons. To illustrate, the SU(4) multiplets in the charm and beauty sector are shown in Fig. 1.1 and 1.2. Their spectroscopic properties and identification then became a challenge both experimentally and theoretically. Today, many of these heavy flavour baryons and mesons are recorded experimentally. Though many of the high orbital excited states of quarkonia (c\bar{c}, b\bar{b}) are known experimentally, in the open flavour sector very few are known. However, the recent experimental trends in the open flavour sectors are encouraging and hope to bring many surprises that pose challenges to understand them. Some of these aspects related to the recent trends in the heavy flavour hadrons properties and related issues will be discussed in the following sections of this Chapter.
Figure 1.1: SU(4) flavour multiplets of baryons.
A natural language for the description of the structure of hadrons is the constituent quark model, where constituent-quark effective degrees of freedom interact via potentials, flux tubes, or are confined to a bag. The notion of the constituent quark comes from phenomenology; for this reason, its definition is necessarily model dependent. The detailed structure of mesons containing $c$ or $b$ quarks has traditionally been a high energy physics subject. However, the heavy quarkonium and hybrid sectors are especially attractive for the study of hadron spectroscopy, since the complications of relativistic quark motion and large decay widths, are of reduced importance. Very interesting results were found in $c\bar{c}$ mesons above open-charm threshold, such as a possible $D^*\bar{D}^*$ molecular state. In view of recent theoretical and experimental results on exotics, led to initiate new experiments at different high energy facilities like the high-statistics $e^+e^-$ “tau-charm” machine at Beijing, China.

Heavy-Light flavour meson systems ($D$, $D_s$, $B$, ...) have already been studied in detail using heavy quark effective theory (HQET), especially their weak transition amplitudes, described through the Isgur-Wise function [2]. Many other interesting predictions of HQET have motivated the experimentalist to look for strongly unstable heavy-light states. As flavour is conserved in strong interaction the open flavour hadrons decays are determined by weak interaction processes. For example, the CP-Violation studies at high energy machines are the high priority experiments. Recently, complications in the determination of CP phases due to strong final state interaction (FSI) effects have been realized. Studies of $D$ and $D_s$ decays have confirmed experimentally that these FSI phases are important [1, 2]. A better understanding of strong interaction effects in the CP-relevant are expected. Similarly, determination of Cabibbo-suppressed CKM matrix elements and $D\bar{D}$ mixing parameters will require an understanding of strong interaction effects among the light hadron decay products of heavy-light flavour mesons [4].

Recently many new excited charmed baryon states have been discovered by SELEX at Fermilab (USA), CLEO at Cornell storage ring (Cornell, USA), BaBar (USA) and Belle (KEK-Japan). Heavy baryons have narrow widths and they are hard to produce. As products in the decays of heavy mesons or in hadron collider, the cross sections to produce them are small. There are no resonant production mechanisms as for heavy mesons. So, heavy baryons always have been obtained by continuum production [5]. Furthermore, none of the quantum numbers, listed in the Particle Data Group (PDG) book, are really measured, but are assignments based on quark model
Figure 1.2: SU(4)\textsubscript{flavour} multiplets of mesons.
At present, only for single-charmed baryons masses of ground states as well as many of their excitations are known experimentally with rather good precision. If the spectrum of the single charmed baryons is well known, it will provide us a framework for studying baryons with bottom quark and help for in understanding the doubly or triply charmed baryons. The doubly heavy baryons open new challenges in the study of heavy quark dynamics in various aspects such as the interplay of strong and weak interactions in decays as well as the confinement mechanism. The dynamics of quarks in double heavy flavour baryons combine two opposite effects of the slow relative motion of two heavy quarks and the fast motion of the light quark. They provide scope for testing ideas developed for single heavy baryon physics, such as the predicted hierarchies in lifetimes and semileptonic branching ratios and give us more room to explore predictions of exotic tetra- and pentaquark states. Moreover, the spectroscopy of baryons containing two heavy quarks is of interest because of similarities both to a quarkonium state ($Q\bar{Q}$) and to a heavy-light meson ($\bar{Q}q / Q\bar{q}$). The first observation of a candidate for a double charm baryon has reported by the SELEX collaboration, that decays to $\Lambda^+ K^- \pi^+$ [9]. Future high luminosity experiments are expected to provide more light in this sector of double and triple heavy flavour baryons.

The most basic elements of baryon spectroscopy are its ground state properties: mass, spin, magnetic moment and charge radii. The main goal of modern experiments are the full determination of the spectrum of excited states, identification of possible new symmetries in the spectrum, and illuminating the microscopic structure of states that are nominally built of three valence quarks. As mentioned above, the establishment of SU(3) symmetry was a key result in particle physics at the beginning of baryon structure studies. Advanced experimental capabilities and the ability to solve models with close approximation to QCD now allow far deeper understanding [4].

The other major direction is to use spectroscopic information to learn about the underlying forces that act on quarks in baryons. The mass spectrum displays the ordering of states by spin, parity, and flavor. This can be thought of as empirical splitting that provides information about the effective degrees of freedom and has already provided the basis for many empirical models. The decay branching fractions of excited baryons to various asymptotic states and the corresponding angular distributions provide more detailed filters for models. In recent years, several labs have
initiated vigorous programs in baryon spectroscopy. The use of modern detectors with large acceptance—effectively electronic bubble chambers—and high statistics capabilities will provide important advances in our knowledge of heavy flavour baryon spectroscopy. The important new detectors are just starting to publish data, so although the picture is far from complete, the quality of the new results has been demonstrated [1].

It is now clear that nature has given us an incredible empirical gift, as is evident in the slowly varying hadron mass gaps between orbitally-excited (e.g. $^3P_2 - ^3S_1$) and spin-excited (e.g. $^3S_1 - ^1S_0$) mesons as the quark mass evolves from heavy to light quarks (or from above the QCD scale to below it). This surprising feature motivates the use of nonrelativistic phenomenological quark models over the full range of quark masses, despite the fact that the model has no rigorous justification in light quark systems. Nevertheless, the success of the phenomenological models indicate that some of the properties of constituent quarks, such as their effective masses and sizes, may be related to QCD. This is where the connection of models to experiment is the closest. Relating model predictions to data involves the calculation of observable through models of reaction dynamics, the estimation of final-state interactions and the effects of open decay channels on hadron masses and properties. Such attempts should ultimately evolve into a description of QCD at the hadronic scale. More recently, advances in computer technology allowed considerable improvement in the studies of hadrons using lattice QCD techniques. One may anticipate that many of the basic aspects of QCD will be known through lattice studies and these results may be abstracted by model builders for application in the regimes of high-mass excitations and scattering, which are not easily accessible to lattice studies. In the near future, we expect that progress in hadron spectroscopy will follow from a synthesis of results from lattice gauge theory, phenomenological quark models and high-statistics experiments on several hadronic states [3].

The theoretical foundations and extensive experimental tests of the standard model in general and QCD in particular are so compelling that the focus is not on testing QCD but rather on understanding QCD. One of the objective of this field is to determine the parameters of QCD. In this scheme, the fundamental scale, $\Lambda_{QCD}$, which sets the scale for all strong interaction phenomena, the masses of quarks which ultimately control details of hadron spectroscopy, and the QCD vacuum parameter controlling the violation of CP symmetry etc., need to be determined precisely [1].
Other objectives of this field include the understanding of the origin and dynamics of confinement by which the fundamental constituents of composite hadrons (the quark and gluons) cannot be removed from hadrons and examined in isolation. We need to understand from first principles how the colour interaction among the quarks leads to the confinement of color charge, how do they evolve with energy scales and the role that they play in the structure and dynamics of hadrons. Experimental and theoretical exploration of the full spectrum of states composed of heavy flavour will be an important tool in attaining this understanding.

1.2 Recent Experimental Facilities for Heavy Flavour Physics

Spectroscopy of heavy flavour hadrons has attracted considerable interest in recent years due to many experimental facilities such as the BES at the Beijing Electron Positron Collider (BEPC), E835 at Fermilab, CLEO at the Cornell Electron Storage Ring (CESR) etc., worldover. They have been able to collect huge data samples in the heavy flavour sector. Where as B-meson factories, BaBar at PEP-II and Belle at KEKB are working on the observation of new and possibly exotic hadronic states. All these experiments are capable of discovering new hadrons, new production mechanisms, new decays and transitions and in general will be providing high precision data sample with better statistics at higher confidence level. In near future, even larger data samples are expected from the BES-III upgraded experiments, while the B factories and the Fermilab Tevatron will continue to supply valuable data for few more years. Later on, the LHC experiments at CERN, Panda at GSI etc., will be accumulating large data sets which will offer greater opportunities and challenges particularly in the field of heavy flavour physics [10, 11].

An essential foundation for progress in hadronic physics is the aggressive exploitation of present facilities and development of new ones, with a clear focus on experiments that provide genuine insight into the inner workings of QCD. In the near term, it must be a high priority to fully exploit existing modern facilities. At Jefferson lab (JLab) a 12 GeV energy upgrade will open new windows in heavy hadron physics. At BNL completion of the detectors will make possible full exploitation of the unique hadron beams at Ring Imaging Cherenkov detector (RICH). In addition to the present
Table 1.1: Experimental facilities for heavy flavour hadrons studies

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<th>Experimental</th>
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| BABAR        | $e^+e^-$ collider | • CP violation in the $B$ meson system.  
• Precision determination of CKM matrix.  
• Heavy hadron spectroscopy and form factors.  
• Heavy hadron production, Exclusive $B$ decays, etc., [12]. |
| BELLE        | $e^+e^-$ collider | • Hadron production.  
• The time-dependent CP asymmetries in the decay of $B$-mesons.  
• The production and decay of charmonium states [13]. |
| TEVATRON     | $p\bar{p}$ collider | • Heavy quark hadrons like excited $b$-mesons and $b$-baryons.  
• Electroweak production.  
• Quarkonium decays.  
• Hadron decays into charmonia and $B_c$ studies [14]. |
| SELEX        | $p\bar{p}$ collider | • High statistics studies of charm baryons.  
• $D$ and $D_s$ mesons state.  
• Charm hadroproduction.  
• Hyperon Physics.  
• Exotic state of hadrons [3]. |
Table 1.2: Experimental facilities for heavy flavour hadrons studies

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<th>Experimental Type</th>
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| CLEO-c $e^+e^-$ collider | • Charmonium physics.  
• Measurements of branching fractions and form factors of $D$ and $D_s$ decays.  
• Searches for new particles and new physics beyond SM.  
• Exploring QCD and hadronic physics through studies of the spectrum and decay of $c\bar{c}$ states below open-charm threshold [15]. |
| Focus $p\bar{p}$ collider | • High precision studies of charm semileptonic decays, hadronic charm decays (branching ratios and Dalitz analyses).  
• Lifetime measurements of the all charm particles.  
• Searches for mixing CP violation rare and forbidden decays.  
• Spectroscopy of excited charm mesons and baryons, pentaquarks, double charm baryons and charm production asymmetry measurements [16]. |
| BESIII $e^+e^-$ collider | • Light hadron spectroscopy  
• Charmonium physics.  
• Electro-Weak physics from charm mesons.  
• QCD and hadron physics.  
• Tau physics, search for new physics and rare decays.  
• $D$-physics.  
• $D^0 - \bar{D}^0$ oscillations and $CP$ asymmetry.  
• Study of exotic charmonium states and its transitions [17]. |
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<th>Experimental Type</th>
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| **PANDA** p ¯p collider | • Test of QCD, Nucleus-nucleus collisions, nuclear structure and nuclear astroparticle investigations with nuclei far off stability.  
• High density states (QGP).  
• Structure of hadrons in the charmonium mass range as well as the spectroscopy of hypernuclei.  
• Production of baryon-antibaryon pairs [18]. |
| **CMS and ALICE** p ¯p collider | • Searches for Higgs and new physics beyond standard model.  
• Heavy flavor physics in terms of hadron production and decays.  
• Study the $J/\psi$ reconstruction and decay of $B_c$ meson and its lifetime.  
• Production and detection of quarkonia in heavy ion collisions.  
• Investigate the properties of strongly interacting matter.  
• Open charm and open beauty production [19]. |
| **ATLAS and LHCb** p ¯p collider | • Study of QCD at unprecedented energy scales (TeV).  
• Study of heavy flavor hadrons including quarkonium states.  
• Production polarization of the $\Lambda_b$ and $J/\psi$.  
• $D$ – $\bar{D}$ oscillations.  
• $B$ Physics including CP violation studies, rare decays.  
• Studies of heavy flavor hadrons, including quarkonia and excited states in the $B_c$ family [20]. |
dedicated facilities supported by the nuclear physics program, significant opportunities exist to use lepton and hadron beams at other accelerator facilities, for example at Fermilab and CLEO. It is important to aggressively utilize capabilities of these beams to address key issues in hadronic physics. In the longer term, a high luminosity electron ion collider would be a powerful new microscope for the examination of hadronic structure. To develop the optimal capabilities in a timely way, research and development of accelerator and detector technology will be necessary. Some of the experimental research group actively involved in the heavy flavour physics are listed in Tables 1.1, 1.2 and 1.3 with their physics prospects.

1.3 Theoretical Status of Heavy Flavour Hadrons

Quantum Chromodynamics (QCD) is the theory of the strong interactions: Its property of asymptotic freedom [21] allows one to interpret deep inelastic scattering experiments [22] in terms of point like hadron constituents, and permits perturbative calculations of short-distance phenomena. However, we are far from understanding how it works at long distances governing the spectra of hadrons and predicting low energy properties of strongly interacting matter still represents a serious theoretical challenge. Many hadrons discovered recently have unexpected properties and we need to understand hadron spectra in order to separate electroweak physics from strong-interaction effects. Moreover, we may need to use our experience with QCD in dealing with any non-perturbative effects encountered at higher energies such as those to be probed by the Large Hadron Collider (LHC). The understanding of electroweak symmetry breaking may well require non-perturbative techniques at TeV scales similar to those useful for hadron spectroscopy at GeV scales. Sharpening spectroscopic techniques even may help to understand the intricate structure of masses and transitions. The QCD scale is \( \sim 200 \text{ MeV (momentum)} \) or \( \sim 1 \text{ fm (distance)} \), where perturbation theory cannot be used. Although lattice gauge theories are, in principle, the way to describe effects in this regime, several other methods can provide information, especially for multi-quark and multi-hadron problems which are not yet feasible with lattice techniques. A new initiative in lattice QCD at the scale of 10 Tflops is required to exploit new advances in lattice field theory.
1.3.1 The Theoretical Approaches

Lattice QCD provides an approach to calculate the properties of hadronic bound states of strongly interacting matter from first principles and where the uncertainties can be reduced in a systematic way. Indeed no other method has surfaced which can lay claim to a similar ‘universal’ validity. On the other hand there are other theoretical technologies that provide a ‘first principles’ treatment of nonperturbative dynamics, even though in a more restricted domain like the chiral invariance and heavy quark expansion (HQE).

Low energy nonperturbative QCD can either be modelled or simulated on the Lattice. Lattice gauge theory methods are particularly powerful in heavy quark physics when combined with effective field theories (EFTs). Lattice QCD input significantly increases the predictive power of EFTs as more and more low energy parameters can be calculated reliably directly from QCD and less fits to experimental data are required for this purpose [3].

Key advances over the past decade in understanding how to discretise QCD accurately onto a space-time lattice are now allowing to do this by bringing realistic calculations within the power of supercomputers [23]. One can now calculate the masses of hadrons with small width and simple decay matrix elements that include at most one such hadron in the final state. Lattice QCD thus can make an important contribution to flavor physics and the determination of elements of the Cabibbo-Kobayashi-Maskawa matrix. Experiments can now achieve errors of few percent on weak decay rates (and has already done this on mixing rates) for bottom and strange hadrons and needs theoretical input for the Standard Model prediction to extract the appropriate CKM matrix element. Lattice QCD then provides a very natural and accurate way to determine the parameters of QCD [24]. There are practical limitations in the available computing power to achieve these desirable goals. The theoretical approach tries to describe heavy quarkonium with QCD based calculations and/or approximations aims at obtaining the spectrum of heavy quarkonium from QCD. This is in principle more complicated than obtaining masses of light mesonic states since an additional scale corresponds to the mass of the heavy quark $m_Q$, enters the calculation. If we assume that $m_Q$ is much larger than any other scale in the system, in particular $\Lambda_{QCD}$, the heavy quarks and antiquarks are expected to move slowly about each other at a relative velocity $v/c \ll 1$. The system becomes non-relativistic.
and hence splitting between states with the same quantum numbers are expected to be of size $\sim mv^2$ whereas hyperfine splitting are of order $\sim mv^4$, by analogy to QED bound states (where $v \sim \alpha$). If $v^2 \sim 0.1$, as expected in ground state bottomonium, a direct (lattice) QCD calculation requires a precision significantly better than 10\% to detect spin-averaged masses and of more than 1\% to resolve fine structure splitting. Moreover, all these scales have to be resolved on one and the same lattice, necessitating many lattice points. This is to be compared with light quarkonium where the splittings are a leading order effect. Consequently, calculating the heavy quarkonium spectrum from lattice QCD requires a tremendous computational effort, which in some cases can be somewhat improved with the introduction of anisotropic lattices.

1.3.1.1 Effective Field Theories

Direct QCD calculations in multiscale problems are extremely difficult, no matter if one uses perturbation theory or lattice. Attempts are being made to construct a simpler theory (the effective field theory (EFT)), in which less scales are involved in the dynamics and which is equivalent to the fundamental theory (QCD) in the particular energy region where heavy quarkonia states lie. The clues for the construction are: (i) to identify the relevant degrees of freedom, (ii) to enforce the QCD symmetries and (iii) to exploit the hierarchy of scales. Typically one integrates out the higher energy scales so that the lagrangian of the EFT can be organized as a series of operators over powers of these scales. Each operator has a matching coefficient in front, which encodes the remaining information on the higher energy scales. The matching coefficients may be calculated by imposing that a selected set of observables coincide when are calculated in the fundamental and in the effective theory.

Heavy quarkonium systems have been a good laboratory to test our theoretical ideas since the early days of QCD [3]. Based on the pioneering work of Caswell and Lepage [25], a systematic approach to study such systems from QCD has been developed over the years which makes use of effective field theory techniques and is generically known as Non-Relativistic QCD (NRQCD) [26]. NRQCD has been applied to spectroscopy, decay and production of heavy quarkonium. The NRQCD formalism for spectroscopy and decay is very well formulated, so that NRQCD results may be considered QCD results up to a given order in the expansion parameters (usually $\alpha_s(m_Q)$ and $1/m_Q$, $m_Q$ being the heavy quark mass). NRQCD is the (first) effective theory relevant for heavy quarkonium. NRQCD is equivalent to the full QCD but it simpli-
fies QCD by taking a nonrelativistic expansion and by reducing the number of the energy scales. Out of the four components of the relativistic Dirac fields describing the heavy quarks (antiquarks) only the upper (lower) are relevant for energies lower than $m_Q$ (no pair production is allowed). Hence a two component Pauli spinor field is used to describe the quark (antiquark). The hierarchy of scales exploited in NRQCD is $m_Q \gg m_Q v, m_Q v^2$ and $\Lambda_{QCD}$. The remaining hierarchy $m_Q v \gg m_Q v^2$, is exploited using a further effective theory called potential NRQCD (pNRQCD) [27, 28]. Extensive review on both NRQCD [3] and pNRQCD are available in literature [27, 28]. Unlike HQET, NRQCD does not enjoy a homogeneous counting. This is due to the fact that the scales $m_Q v, m_Q v^2$ and $\Lambda_{QCD}$ are still entangled. Even though a counting was put forward in [26], the so called NRQCD velocity counting, which has become the standard book keeping for NRQCD calculations, there is no guarantee that it holds for all the states, and hence there is a problem on how to make a sensible organization of the calculation for a given state. There are two approaches which aim at disentangling these scales, and hence to facilitate the counting. The first one consist of constructing a further effective theory by integrating out energy scales larger $m_Q v^2$. This is the pNRQCD approach first proposed by [27]. The second one consist in decomposing the NRQCD fields in several modes so that each one has a homogeneous counting. This is the vNRQCD approach first proposed by [29, 30]. The scale $\Lambda_{QCD}$ has not been discussed so far in this approach, and in fact, a consistent formulation has only become available recently [31, 32].

The NRQCD formalism provides a solid QCD-based framework where heavy quarkonium spectroscopy and inclusive decays can be systematically described starting from QCD. An NRQCD factorization formalism has also been put forward for semi-inclusive decays, inclusive production and, more recently, exclusive production, which, in spite of its successes, is not so well understood theoretically. Nevertheless, remarkable progress has been made recently concerning the structure of the factorization techniques for inclusive processes and the relation to the light-cone formalism for exclusive ones [33].

1.3.2 The Phenomenological Approaches

The phenomenological approach attempts to model what are believed to be the features of QCD relevant to heavy quarkonium with the aim to produce concrete results which can be directly confirmed or falsified by experiment and may guide experimen-
tal searches. Some of the well known phenomenological approaches to study hadron properties bound on its quark-gluon degrees of freedom are Bag models, QCD sum rules, Heavy quark effective theory and potential models. Certain important aspects of these approaches are being discussed in the following sections.

1.3.2.1 Bag Models

The earliest confinement model was the relativistic bag model \[34,35\]. Motivated by field theoretical investigations, one assumes that the physical vacuum as characterized by some microscopic structure which is “normal phase” outside hadrons, cannot support the propagation of quark and gluon fields. The vacuum acts like a strange medium against hadronic constituent fields, though Lorentz invariance will be maintained. In such a vacuum, a small domain of different phase may be formed. It is like boiling the vacuum and creating small bubbles with a characteristic hadron size. Inside the bubble, quark and gluon fields can propagate freely. To picture the hadron, then as a small domain in the new phase with quark and gluon as constituents. This is the bag and the boundary surface of the bag between the two phases is impermeable against the colour fields, therefore they can’t penetrate into the normal phase of the vacuum. The impermeability at the surface is expressed in the form of boundary conditions for the colour fields \[36\].

In the naive bag model, hadrons are considered as spherical bag and the quarks are Dirac particles permanently confined within the volume of the bag which has a finite radius equal to that of the hadron size. It has been successful in describing the light hadron spectroscopy (uds sector). The Bag model gives simple description of the hadronic systems, there is no derivation of such models from the fundamental theory of QCD. Like many other phenomenological models, it also does not preserve the chiral symmetry which is considered as a fundamental symmetry of the strong interaction.

1.3.2.2 QCD Sum Rules

A phenomenological treatment of nonperturbative effects of QCD is the technique of QCD sum rules. This method is extremely useful in calculating the lowest mass hadron bound states or determining effective coupling constants. In addition, QCD sum rules offer some surprising insights into the internal wave functions of nucleons
and pions. QCD sum rules attempts to separate perturbative and nonperturbative contributions by a set of phenomenologically effective Feynmann rules. Starting point for QCD sum rules is the operator-product expansion \[37\]. The one pion exchange gives a general form for the quantities of interest, and QCD sum rules are a phenomenological procedure for evaluating the matrix elements of the operator that occur. QCD sum rules start from the fact that vacuum polarization tensor can be described at the hadronic level. It invokes colour condensates to describe the nonperturbative effects of QCD. It consistently describes a plethora of hadronic data, all of them with a typical accuracy of about 20\% \[38\]. However applicability of QCD sum rules other than hadronic masses is not trivial.

1.3.2.3 Heavy Quark Effective Theory (HQET)

One of the approach to mimic the nonperturbative aspect of strong interaction at the hadronic domain is provided by heavy quark effective theory (HQET) put forward by Isgur and Wise \[39\]. The central idea of the heavy quark effective theory is very simple. It is useful when dealing with hadrons composed of one heavy quark and any number of light quarks. More precisely, the quantum numbers of the hadrons are unrestricted as far as isospin and strangeness, but are $±1$ for either bottomness or charmness but not both. The success of the constituent quark model is indicative of the fact that inside the hadron, strongly bound quarks exchange momentum of the order of a few hundred MeV.

We can think of typical amount $\lambda$ by which the quarks are off-shell in the nucleon as $\lambda \simeq m_p/3 \simeq 330$ MeV. In a heavy hadron, the same intuition can be imported and again the light quarks are very far off-shell, by an amount of order $\lambda$. But, if the mass $m_Q$ of the heavy quark is large, $M_Q \gg \lambda$, then, in fact, this quark is almost on-shell. Moreover, interactions with the light quarks typically change the momentum of $Q$ by $\lambda$, but change the velocity of $Q$ by a negligible amount, of the order of $\lambda/m_Q \ll 1$. It therefore makes sense to think of $Q$ as moving with almost constant velocity and this velocity is the velocity of the heavy hadron. In the rest frame of heavy hadron, the heavy quark is practically at rest. The HQET is a method for giving a procedure for making explicit calculations, but more importantly, it turns the statement ‘$m_Q$ is large’ into a systematic perturbative expansion in powers of $\lambda/m_Q$. Each order in this expansion involves QCD to all orders in the strong coupling $g_s$. According to HQET, the properties of heavy hadrons are independent of the spin and mass of the
heavy source of colour. This statement appears in the theory as approximate internal symmetries of the Lagrangian.

One can see that these statements apply just as well to a very familiar and quite different system: the atom. The role of the heavy quark is played by the nucleus and that of the light degrees of freedom by the electrons. An obvious distinction between the atomic and hadronic system is that in hadronic system, the configuration of the light degrees of freedom is non-computable due to the nonperturbative nature of the strong interactions. The methods described by HQET avoid the need for a detailed knowledge of the configuration of light degrees of freedom. The difficulty then here is that the range of predictions and its applicability is restricted to light-heavy hadrons. HQET is successfully applied in the study of leptonic and semileptonic decays of heavy mesons [40]. It suggests a method that may afford higher accuracy in the extraction of Kobayashi-Maskawa matrix (KM matrix) elements (such as |$V_{ub}$|) from exclusive decays. Because of its simplicity and successes, it is being accepted as one of the important theoretical tools for the study of light-heavy flavored hadrons. A detail review on the developments in HQET is available in literature [41].

1.3.2.4 Potential Models

One of the basic tools of the phenomenological approach is potential models, both non-relativistic and relativistic. The use of non-relativistic potential models is justified by the fact that the bottom and, to a lesser extent, the charm masses are large in comparison to $\Lambda_{QCD}$, the typical hadronic scale. Hence a quantum mechanical description of the system based on two heavy quarks interacting through a suitable potential appears reasonable. The potential is usually chosen in a way that short distances coincides with the weak coupling QCD one-gluon exchange Coulomb potential and in the long range it incorporates confinement, for instance, by including a linearly rising potential. Since relativistic effects appear to be sizable for some states, mostly in charmonium, models incorporating some relativistic kinematics are also being used [42]. Different models of quark confinement may result in different classes of relativistic corrections. For states close to and beyond the two heavy-light meson threshold, the potential models have to be complemented with these extra degrees of freedom in order to account for possible mixing effects. Hybrid states which are expected from QCD should also be incorporated by hand.
The potential models are either motivated by QCD or inspired by experimental facts. The methods of analysis used are very similar to those in atomic physics, where one uses either nonrelativistic or relativistic quantum mechanics. The essential features of some of the popular confinement potentials which have been used to study the hadron properties are briefly described here. Though the behavior of the interquark potential at short range (small r) is known to have 1/r dependence (See Appendix-A) at large (hadronic scale), QCD perturbation theory break down and we have the confinement of quarks. Thus unlike the short range part of the potential, the long range part cannot be calculated on perturbative QCD as the QCD coupling constant becomes large in this region. Perturbative QCD gives no hint of intrinsically nonperturbative phenomena such as color confinement. The phenomenological models developed for the confinement of quarks to study the hadrons are the nonrelativistic quark models (NRQM) [39]. In NRQM, quarks are treated as phenomenological constituent particles and are ascribed large effective masses. In these models, quarks are assumed to be confirmed within the hadron under the influence of a nonrelativistic confinement potential of the type: \( V(r) = a/r + br \) or \( ar^2 \). But a particle of mass “m” confined in a volume of radius R has momentum \( \sim 1/R \) by uncertainty principle. Thus, its kinetic energy is very much less than m only if \( mR \gg 1 \). Since the average kinetic energy of the heavier quarks (i.e. c, b) is smaller than their masses, the NRQM provides a better description of the heavy flavour hadrons. The short coming is overlooked in NRQM, since they give a good description of the static properties of the excited hadron spectra [43]. Some of their results will be compared with the results of the present study on hadronic masses in later chapters of this thesis. In the NRQM, the spurious excitation of the center of mass motion can be eliminated easily unlike the bag model. Other relativistic approaches employed [44, 45, 46, 47, 48, 49] for the study of hadrons are available in literature.

Inspired from the Lattice calculations, linear confinement potential have been used by many authors [50, 51] for the study of hadronic properties. The linear plus coulomb potential has been widely used in the heavy flavour sectors. The potential is given as [52, 53]

\[
V(r) = -\frac{4 \alpha_s}{3} \frac{1}{r} + Ar
\]

where \( \alpha_s \) and A are the strong coupling constant and model spring constant respectively. This potential is motivated by the fact that the theory of the strong interactions (QCD) has asymptotic freedom at small distances and confinement at large distances. Here, r is the separation between the quarks. At small r, the “one-gluon-exchange”
is dominant and is represented by the coulomb term. For large $r$, according to the flux tube model (or the string model) the potential increases linearly and hence, the second term. Such a form is indicated by lattice calculations. In the quench approximation, for heavy quarks, the constant $\alpha_s$, $A$ and the so called “constituent quark masses” are fixed by fitting the experimental data.

Table 1.4: Various Potential Models

<table>
<thead>
<tr>
<th>Nonrelativistic [52]</th>
<th>$V_{NR} = -\frac{4}{3} \frac{\alpha_s}{r} + A r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relativistic [47]</td>
<td>$V_{NR} = -\frac{4}{3} \frac{\alpha_s}{r} + A r + V_0$</td>
</tr>
<tr>
<td>Quigg–Rosner (Logarithm) [54]</td>
<td>$V_{NR} = A \ln(r/r_0)$</td>
</tr>
<tr>
<td>ERHM [55]</td>
<td>$V(r) = \frac{1}{2}(1 + \gamma_0)A^2 r^2 + B$</td>
</tr>
<tr>
<td>Martin [56]</td>
<td>$V_{NR} = A + B r^{0.1}$</td>
</tr>
<tr>
<td>Buchmüller and Tye [57]</td>
<td>$V_{NR} = -\frac{4}{3} \frac{1}{(2\pi)^3} \int d^3q \exp(i \mathbf{q} \cdot \mathbf{x}) \frac{4\pi \alpha_s(q^2)}{q^2}$</td>
</tr>
<tr>
<td>Falkensteiner [58]</td>
<td>$V_{NR} = -\frac{4}{3} \frac{\alpha_s}{r} \text{erf}(\sqrt{\pi} A r) + A r$</td>
</tr>
</tbody>
</table>

Though there exist many potential models with relativistic and nonrelativistic considerations employed to study the hadron properties based on its quark structure [33, 47, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67], the most commonly used potential is the coulomb plus linear power potential, $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$, with the string tension $\sigma$. Such a form is supported by lattice QCD calculation [68, 69]. However, for the higher excited mesonic states it is argued that the string tension $\sigma$ must depend on the $Q\bar{Q}$ separation [70, 71]. This corresponds to flattening
of the confinement potential at larger $r$ ($r \geq 1 \text{fm}$). Moreover the analysis based on Regge trajectories for meson states suggests the confinement part of the potential to have the power $\frac{2}{3}$ instead of 1 \cite{72, 73}. This has prompted us to choose a power form for the confining part of the interquark potential and study the properties of heavy flavour $Q\bar{Q}$ systems by varying the power around 1.0.

The experimental mass spectra of heavy flavoured mesons were described in the framework of phenomenological non-relativistic as well as relativistic potential models such as Buchmüller and Tye potential (BT) \cite{57}, Power Law (PL) potential \cite{63}, Logarithmic potential (Log) \cite{64}, Cornell potential (Cornell) \cite{52} etc. For the present study, we consider these models along with other contemporary potential models such as Relativistic Harmonic Model (RHM) \cite{45, 46, 48, 49} and coulomb plus a general power potential with varying power index $\nu$, $(CPP_\nu)$ \cite{59, 60, 74, 75, 76, 77}. Some of the potential models employed to study the hadron spectroscopy are briefly summarized in Table 1.4.

### 1.3.2.5 Coulomb Plus Power Potential ($CPP_\nu$): Generality of Potential Models

The Coulomb Plus Power Potential ($CPP_\nu$) is expressed in terms of a vector (Coulomb) plus a scalar (confining) part given by \cite{59, 60, 74, 75, 76, 77}

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + Ar^\nu$$ \hspace{1cm} (1.2)

This potential belong to the special choices of the general potential, $-Cr^{-\alpha} + Dr^\beta + V_0$ \cite{78, 79, 80, 81} with $V_0 = 0$, $\alpha = 1$, $\beta = \nu$. There exists many potentials of this general form \cite{78}, for example, Cornell potential \cite{53} corresponds to $\alpha = \beta = 1$, Lichtenberg potential \cite{82} corresponds to $\alpha = \beta = 0.75$, Song-Lin potential has $\alpha = \beta = 0.5$ and the Logarithmic potential \cite{64} of Quigg and Rosner corresponds to $\alpha = \beta \to 0$ etc., while, Martin potential \cite{63} corresponds to $\alpha = 0$, $\beta = 0.1$ \cite{83, 84}, Grant-Rosner and Rynes potential corresponds to $\alpha = 0.045$, $\beta = 0$ and Heikkilä, Törnquist and Ono potential corresponds to $\alpha = 1$, $\beta = 2/3$ \cite{85}. Most of these potentials have already been employed for the study of hadron properties \cite{83, 84, 80, 87, 88}. Potentials with choices $\alpha$ and $\beta$ in the range $0 \leq \alpha \leq 1.2$ and $0 \leq \beta \leq 1.1$ are also being explored \cite{81}. This potential has already been employed to the study of heavy flavour mesons by \cite{74, 59} using the variational approach. However, for the present study we employ $CPP_\nu$ potential and solve the nonrelativistic eigenvalue problem of the hamiltonian
using the numerical approach [76].

Many of the potential models discussed so far provide a very good fit to the spectra of either the heavy flavour hadrons or the low flavour hadrons. The reason is that all the above potentials coincide apart from an arbitrary constant, in the region $0.1 < r < 1$ fm. Many of the questions are unanswered in potential models. The relation of the mass parameter, and the “constituent mass” to QCD is unknown. Different models use different mass parameters. For the charm quark, the choices for the constituent mass ranges from 1.1 GeV to 1.9 GeV. For the bottom quark, the range chosen is from 4.5 GeV to 5.2 GeV.

Another drawback in most of the potential models is their inability to explain the spectrum, leptonic decays, radiative transitions and hadronic decays satisfactorily using the same set of parameters [52]. It is observed that when the parameters are adjusted so as to get correct leptonic width, the radiative transition rates become worse and vice versa. Only the results of Godfrey and Isgur for the spectrum are in good agreement with experiment. They included an annihilation interaction term in their model, which they believe is important for light quarks. They did not include, however, the channel-coupling effect which may be important for excited states above threshold. Most of the authors of potential models believe that the channel-coupling effect is important in obtaining good results for the levels above threshold. Even in the prediction of the hadrons masses, these models fail to have a unique scheme which can accommodate all the flavour sectors. Hence, one must look for alternate models which have the unique features providing the decay properties of mesons with different flavour combinations with the same set of model parameters that explain their spectra.

In short, it is expected that parameters of the model deduced from the spectroscopy must be able to predict other features such as the decay width, transition rates etc., of the hadron. Thus our endeavor here would be to study the spectroscopic properties of the heavy flavour hadrons to identify the model parameters including the type of interquark potential and effective constituent quark masses that explains the spectral properties as well as the decay properties including the weak interaction properties of the heavy flavour hadrons.
1.4 Recent Observations and Challenges in Heavy Flavour Physics

With charm quarks to the SU(3) octet and decuplet of $u,d,s$ quarks gives 18 baryons with one $c$-quark, 6 baryons with two $c$-quarks and one baryon $\Omega^{++}_{ccc}$ with three $c$-quarks. Prior to 2005, most of the charm baryon results came from CLEO and ARGUS from $e^+e^-$ annihilations in the Upsilon(4S) region, and from FOCUS at Fermilab and NA38 at CERN. Now that the B–factories are in operation, many baryons are being detected. BaBar has reported the discovery of $\Lambda_c(2940)$ and $\Omega_c(2770)$, and Belle has reported $\Sigma_c(2800)$, $\Xi_c(2980)$ and $\Xi_c(3080)$. These are clean-cut states with small widths. (i.e. $\Gamma(\Xi_c(3080)) = 6.2$ MeV!) In the mesonic sector, CLEO [89] and Belle [90] find a broad $1^+$ candidate in the range 2420–2460 MeV, while Belle and FOCUS [91] find broad $0^+$ candidates near 2300 and 2400 MeV, respectively.

The main thrust in the study of the open flavor mesons is weak interactions, decay constants, form factors, and CKM matrix elements, and the Standard Model. CLEO and CDF, DØ, Belle and BaBar have been working hard on these measurements, and comparison with lattice predictions. So, far the greatest additivity in strong interaction physics has been in the charmonium region around $\sim$3–5 GeV energy scale. Over the years tremendous activity followed at SLAC at Fermilab, DESY at Germany and more recently at Fermilab, CLEO, and BES in laying down the QCD–based foundation of quarkonium spectroscopy. BES and CLEO have made many high precision measurements of decays of bound charmonium states in recent years [92].

A close examination of the spectroscopy of charmonium states will reveal that most of what was discovered and studied until recently was about spin–triplet states, the $\psi(3S_1)$, $\chi_{cJ}(3P_J)$ states of charmonium and $\Upsilon(3S_1)$, $\chi_{bJ}(3P_1)$ states of bottomonium. The spin–singlet states were too difficult to access, and remained unidentified (with the exception of $\eta_c(1^1S_0)$). This meant that we had very little knowledge of the hyperfine interaction which splits the spin–singlet and spin–triplet states. Until very recently, all that we knew was the singlet–triplet splitting for $\eta_c(1^1S_0)$ and $J/\psi(1^3S_1)$, with $\Delta M_{hf}(1S) = 117 \pm 2$ MeV. We knew nothing about whether the hyperfine interaction varies with the radial quantum number or quark mass, or what all of it means with respect to the spin dependence of the long range $q\bar{q}$ interaction which is dominated by its confinement part. The breakthrough came in 2003 with the identification of $\eta_c'(2^1S_0)$ by Belle, CLEO and BaBar. The result, $\Delta M_{hf}(2S) = 48 \pm 2$ MeV,
nearly 1/3 of $\Delta M_{hf}(1S)$ came as a surprise as against the old Crystal Ball value, $\Delta M_{hf}(2S) = 92 \pm 5$ MeV. One expects here a possibility of the existence of a long-range spin-spin interaction in the confinement region. The second breakthrough in the understanding of the hyperfine interaction comes from the even more recent identification of the $P$-wave singlet state $h_c(1^1P_1)$, which had eluded numerous earlier attempts. Few years ago, CLEO announced the discovery of $h_c$ in both inclusive and exclusive analysis of the isospin–forbidden reaction

$$\psi(2S) \to \pi^0 h_c, \ h_c \to \gamma \eta_c, \ \pi^0 \to 2\gamma$$

The data, based on $\sim 3$ million $\psi(2S)$, had limited statistical precision, as did a recent E835 attempt. Now CLEO has analyzed their latest data for 24 million $\psi(2S)$. So how can we explain the $\Delta M_{hf}(1P) = 0$ experimental result? Apparently, there are subtle problems connected with the regularization of the spin–dependent interactions, and nobody really knows how to handle these subtleties. The vector states $\psi(3770, 4040, 4160, 4415)$ above the $D\bar{D}$ threshold at 3.74 GeV have been known for a long time. However, little more than their total and leptonic widths was known. Now we know a lot more. CLEO and BES, and more recently Belle, have contributed much new information about their decays. The real excitement in this domain of spectroscopy has come about by the discovery of several unexpected states by the $B$-factories of Belle and BaBar. It began with $X(3872)$, then came the states $X, Y, Z$ with nearly degenerate masses of 3940 MeV. This was followed by $Y(4260)$ and now we have reports of $Y(4360), Y(4660), X(4160)$ and $Z^\pm(4433)$.

Since 2002, SELEX group had reported the double charmed baryons $\Xi_{cc}^+(3519)$, (Belle and BaBar) seems to find any evidence for this baryon. So, the status of double charm baryons is still at the conformity stage. The holy-grail particle $\Omega_{ccc}^{++}$ remains undiscovered so far. We hope that future experiment like PANDA can reach for it. One expects bottom baryons $Λ_b, Ξ_b, Σ_b$, and $Ω_b$ just as the charmed baryons. Before 2006, only one bottom baryon $Λ_0^b$ was known. Now, from CDF and DØ we have $Σ_b^+, Σ_b^*$, and $Ξ_b$. These are extremely challenging measurements, resolving states at $\sim 6$ GeV separated by $\sim 20$ MeV, e.g., $m(Σ_b^*) - m(Σ_b^+) = 21.2 \pm 0.2$ MeV. Heavy quark baryons have shown more life recently due to contributions from the $B$-factories at KEK and SLAC.

After having played a major role in the foundation of QCD, heavy hadron spectroscopy has witnessed in the last few years a renewal of interest led by the many new data coming from the B factories, CLEO and the Tevatron and by the progress
made in the theoretical methods. The remarkable progress at the experimental side, with various high energy machines such as BaBar, BELLE, B-factories, Tevatron, ARGUS collaborations, CLEO, CDF, DØ etc., for the study of hadrons has opened up new challenges in the theoretical understanding of light-heavy flavour hadrons. The existing results on excited heavy-light mesons are therefore partially inconclusive, and even contradictory in several cases. The prediction of masses of heavy-light system for ground state as well as excited state are few from the theory [93, 94, 95, 96, 97, 98, 99]. Also spectroscopy of excited mesons containing beauty quarks is not yet well recorded from the experimental side [100]. Only the lowest 0− and 1− states are well established and recorded in the Particle Data Group (PDG) [6]. The L3 collaboration [101] reported first measurement of masses of the 13P1 and 13P2 of Bq meson as 5670±10±13 MeV and 5768±5±6 MeV respectively. Two years ago, DØ and CDF collaborations have reported results on the spectroscopy of orbitally excited beauty mesons [102]. CDF found two states, 11P1 and 13P2, with masses M(11P1)= 5734 ± 3 ± 2 MeV and M(13P2)= 5738 ± 6 ± 1 MeV. D0 also found the same states but with slightly different masses, M(11P1)= 5720.8 ± 2.5 ± 5.3 MeV and M(13P2) - M(11P1)= 25.2 ± 3.0 ± 1.1 MeV. In the strange sector CDF reported two narrow Bs(13P1) and Bs(13P2) states with masses M(Bs(13P1))=5829.4 MeV and M(Bs(13P2))=5839 MeV while DØ measured only the Bs(13P2), with mass of 5839.1 ± 1.4 ± 1.5 MeV.

Similar progress has been observed in the open charm sector. The BaBar Collaboration reported the observation of a charm-strange state, the D∗sJ(2317) [103]. It was confirmed by CLEO Collaboration at the Cornell Electron Storage Ring [104] and also by Belle Collaboration at KEK [105]. Besides, BaBar had also pointed out to the existence of another charm-strange meson, the DsJ(2460) [104]. This resonance was measured by CLEO [104] and confirmed by Belle [105]. Belle results [105] are consistent with the spin-parity assignments of JP = 0+ for the D∗sJ(2317) and JP = 1+ for the DsJ(2460). Thus, these two states are definitively well established, confirmed independently by different experiments. They present unexpected properties, quite different from those predicted by quark potential models. If they would correspond to standard P−wave mesons made of a charm quark, c, and a strange antiquark, ¯s, their masses would be larger [106], around 2.48 GeV for the D∗sJ(2317) and 2.55 GeV for the DsJ(2460). They would be therefore above the D∗K and D∗κ thresholds, respectively, being broad resonances. However the states observed by BaBar and CLEO are very narrow, Γ < 4.6 MeV for the D∗sJ(2317) and Γ < 5.5 MeV for the DsJ(2460).
For the Upsilon (1−−) states, all we know is their masses, total widths, and branching fractions for leptonic, radiative, and $\Upsilon(nS) \rightarrow \pi^+\pi^-\Upsilon(n'S)$ decays. A scarce $\Upsilon(3S) \rightarrow \omega\chi_b(2S)$ transition has been observed, but huge gaps remain. The recent discovery of the singlet state $\eta_b$ [107] has enhanced the interest in this sector. Many, many extremely interesting questions in hadron spectroscopy remain unanswered at present. However, there is every hope that the upcoming facilities, PANDA at GSI, JPARC at KEK, and the 12 GeV upgrade at Jefferson Laboratory (JLab), will rise to meet the challenges and pose new challenges to the theorists to have serious attention in heavy flavour spectroscopy.

The most challenging theoretical problem at present is the description of states above open heavy flavour threshold. The recent discovery of $X$, $Y$ and $Z$ has made clear that potential models suffer from large systematic uncertainties in this region and that the inclusion of, at least, heavy-light meson degrees of freedom is necessary. Although NRQCD holds in this region, extracting information from it on the lattice is not simple, since besides heavy quarkonium, heavy-light meson pairs and hybrid states populate it. It would be important to develop theoretical tools in order to bring current phenomenological approaches into QCD based ones [92, 108].